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by

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16. ABSTRACT

Estimates of an individual's ozone exposure were generated for a panel of 51 asthmatic study subjects using ambient ozone concentrations, the relationships observed between the ambient concentrations and the concentrations found in each of two broad classes of environments and knowledge of the individual's movement through these locations. These estimates are compared to actual ozone concentrations observed during personal monitoring of 30 of the individuals. Earlier comparisons disclosed that the estimated hourly means were in much better agreement with the observed hourly means than were the ambient hourly values. The hourly maxima observed in the personal monitoring for each of three environments are compared to the exposure estimates. The ability of the exposure model to estimate average hourly exposures for individuals has been previously tested. In the present work, the ability of the exposure model to estimate peak exposures within an hour is evaluated, using measurements of ozone concentration obtained at 5 minute intervals during the personal monitoring program as a standard. One-hour exposure estimates based on fixed site measurements are evaluated as well. Sources of error within the data set are identified but appear to not seriously affect the results. The exposure model produces one-hour estimates which are 7-12 ppb below the observed personal exposures.

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Abstract

Estimates of an individual's ozone exposure were generated for a panel of 51 asthmatic study subjects using ambient ozone concentrations, the relationships observed between the ambient concentrations and the concentrations found in each of two broad classes of environments and knowledge of the individual's movement through these locations. These estimates are compared to actual ozone concentrations observed during personal monitoring of 30 of the individuals. Earlier comparisons disclosed that the estimated hourly means were in much better agreement with the observed hourly means than were the ambient hourly values. The hourly maxima observed in the personal monitoring for each of three environments are compared to the exposure estimates. The ability of the exposure model to estimate average hourly exposures for individuals has been previously tested. In the present work, the ability of the exposure model to estimate peak exposures within an hour is evaluated, using measurements of ozone concentration obtained at 5 minute intervals during the personal monitoring program as a standard. One-hour exposure estimates based on fixed site measurements are evaluated as well. Sources of error within the data set are identified but appear to not seriously affect the results. The exposure model produces one-hour estimates which are 7-12 ppb below the observed personal exposures.

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Introduction

In 1981 researchers at the University of Texas School of Public Health at Houston began an investigation which examined the relationship between air pollution exposures and the occurrence of asthma attacks. Following extensive recruitment and screening, described elsewhere[1], a panel of 51 medically managed extrinsic asthmatics, aged 7 to 55 years, was identified. The study subjects resided in the two Houston neighborhoods, Clear Lake (n=31) and Sunnyside (n=20) and the study period lasted from May through October of 1981. The following is a report of the methods we have developed for estimating individual exposures.

Experimental Methods

Data were recorded by each person twice a day and included occurrence of general symptoms, changes in medication usage, a peak flow respiratory function measure, activity data and asthma-specific symptom data. These health data were summarized for each individual to provide an indication of whether an asthma attack had occurred in the 12-hour period (7 A.M. to 7 P.M. or 7 P.M. to 7 A.M.).[2] Previous studies of ozone and asthma had used air monitoring data from a fixed monitoring station some distance away from residences to describe the exposure each individual received, whether indoors or outdoors. Later, the work of several authors [3,4,5] indicated that exposures differed among "microenvironments". As the use of personal monitors on all the study subjects for the course of the study was not feasible for both technological and cost reasons, it was deemed desirable to obtain exposure estimates for each individual using the microenvironment concept.

Pollutant concentrations in each of certain broad groups of microenvironments were estimated using a regression model which describes the relationship of fixed site measurements to concentrations in these microenvironments. Exposure estimates were developed using the microenvironment-specific relationships and the the study subjects' reports concerning their movement through these microenvironments. The regression models made use of the data obtained from a subset of the study population.

To describe the microenvironment exposures a three-tiered monitoring system was developped. Details of this monitoring system have been presented by Stock et al.[6]. The first level consisted of two fixed site monitoring stations established at the centers of the neighborhoods in which the study subjects were living, Sunnyside and Clear Lake. These stations provided continuous monitoring of several pollutants, including ozone, expressed as one-hour averages. Ozone concentrations were determined using Bendix chemiluminescence analyzers. The stations operated for the duration of the six-month study and were located so that every study subject residence was within 2.5 miles of a fixed site.

The second tier was provided by mobile monitoring station housed in a large van. The same pollutants were measured as at the fixed sites. Measurements were taken outdoors and in each of three indoor locations; the bedroom, kitchen, and den or living room. The indoor/outdoor monitoring

was performed for one week at each of 12 residences. The houses were selected to be as representative as possible of the entire set of study subjects' dwellings, but were not a random or designed sample.

Personal monitoring provided the third tier of the sampling network. Ozone was measured with portable CSI chemiluminescence monitors. Monitoring of ozone was labor intensive, requiring two research assistants to carry the monitors as they followed the study subject on his or her daily routine. A total of 30 of the 51 study subjects were involved in the personal monitoring, each for an average of eight hours a day on two separate days.

The model for ozone will be described here. A strong diurnal variation in ozone concentration was noted in the fixed site and outdoor data. Use of the raw data would be inappropriate as the diurnal variation would tend to cause an overestimation of the fixed-site-to-outdoor relationship, and underestimate the fixed-site-to-indoor relationship. Therefore, the hour- and site-specific means were subtracted from the corresponding hour- and site-specific values to remove most of the diurnal variation. A regression model was used to estimate the relationships. This model is

$$(Y_{hr} - \bar{Y}_{hr}) = B\ (FS_{hr} - \bar{FS}_{hr})$$

where

Y_{hr} = hour specific ozone value (indoors or outdoors)
$\bar{Y}_{hr}$ = hour specific ozone mean (indoors or outdoors)
FS_{hr} = hour specific ozone value at the fixed site
$\bar{FS}_{hr}$ = hour specific ozone mean at fixed site
B = regression coefficient

The regression coefficient is an estimate of the slope of the line relating the fixed site deviation to the outdoor or indoor deviation. A separate regression was performed using the fixed site and mobile van data from each of the 12 houses the van monitored; an estimate of the fixed-site-to-indoor and fixed-site-to-outdoor coefficient was obtained for each house. These residence-specific coefficients were examined for differences which might relate to characteristics of the house; no statistically significant differences were found. The summary coefficients which describe the fixed-site-to-outdoors and the fixed-site-to-indoors relationship were obtained using the random effects assumptions described by Korn and Whittemore.[7] The personal monitoring data were used for model validation and not to construct the original regression equations.

Results

The fixed-site-to-outdoor summary coefficient for all residences is 0.78609, with an R-squared value of 73% and is significant at the $p < 0.001$ level. The fixed-site-to-indoor coefficient is also significant at this level; however the coefficient is extremely small (0.005934) and the R-squared value is only 2.1%. These coefficients were used with the hour-specific fixed site concentrations to provide an estimate of the ozone concentrations in each of the two microenvironment categories. To obtain an estimate of the ozone concentration in either the outdoor or indoor microenvironment, the regression equation is solved for Y_{hr}, yielding

$$Y_{hr} = B \cdot FS_{hr} - B \cdot \bar{FS}_{hr} + \bar{Y}_{hr}$$

This equation reintroduces the diurnal variation removed in the regression analysis. Therefore, there is not a strictly monotonic relation between the fixed site measurement and the exposure estimate.

The exposure model also uses data concerning the movement of the study subjects through microenvironments. Activity pattern data were collected using a section of the 12-hour log shown in Figure 1. For any hour, the study subject could indicate whether he or she was in one or more of the locations on the log. Approximately 60% of the study subjects spent two hours or less outdoors on an average day from 7:00 A.M. to 7:00 P.M.

The exposure model was built using the recorded activity data, the ozone values as measured at the fixed sites, hour specific means (to account for the diurnal variation), and the estimated relationships between fixed site values and ozone values outdoors and indoors. An individual's hourly ozone exposure was based on the subject's location and the estimated ozone concentration in that location during that hour. For this model it was assumed that ozone concentration does not vary among the various indoor locations and that the same holds true for the outdoor locations within the study area. Also, it was assumed that an air-conditioned vehicle had the same concentration as that found indoors, while an open vehicle had the outdoor value. Therefore the several locations in the activity log were treated as two broad categories: indoors and outdoors. These simplifications are required by the limits of the sampling scheme used in the indoor/outdoor monitoring and the required simplicity of the activity log form. Ozone exposure estimates for individuals who were in more than one location during an hour were defined as the mean of the estimated ozone exposures in each of the locations.

An example of the ozone exposure estimation for one 12-hour period is shown in Table I. The fixed site data are representative of what might be found during this time period. Each hour has an exposure estimate associated with it. For example, the fixed site ozone one-hour average of 115 ppb between 1400-1500 hours CDT yields an indoor estimate of 1.8 ppb, and outdoor estimate of 94.6 ppb. During this time period the individual indicated activities indoors and outdoors. Therefore, the estimated exposure during that hour is the average of 94.6 and 1.8, or 48.2 ppb. This estimate is based on an equal amount of time being spent indoors and outdoors, which is equivalent to the one-hour time-weighted average. Over the 12-hour period, the maximum estimated ozone exposure for this individual is 68.9 ppb, at the 1100-1200 period, when the fixed site concentration was 87 ppb. It is this concentration which represents the ozone exposure estimate for this 12-hour period in the analysis of the relationship between ozone and asthma for this individual. For each 12-hour period during the study time, an ozone exposure estimate was developed for each study subject using this method. Each subject had a unique set of exposure estimates.

The exposure model yielded the estimate of the average ozone exposure for each hour. These were compared to the values obtained from the personal monitoring. Two methods of summarizing the personal monitoring data were used. In one approach, these data, which were collected as instantaneous readings at five-minute intervals, were reduced to one-hour averages. The results of the comparisons using these averages have been reported elsewhere[8] and will only be reviewed here. For the current investigation, the maximum exposure experienced in the personal monitoring process in each hour and the location of that maximum were used. This exposure may have been only momentary and may not be representative of

exposures during the entire hour. For purposes of comparison, we have used the ambient ozone concentrations at the fixed site.

To measure the accuracy of the exposure estimates, two measures were calculated, the mean difference and the mean-squared difference. If the differences center around zero the mean difference may be small, but the model may still have a high degree of error, which the mean-squared difference will detect. In these analyses the personal monitoring exposures and locations are regarded as the truth against which to evaluate the exposure estimates. The ability of the exposure estimate to detect a maximum ozone exposure within a clock hour was examined because maxima are used in the analytic model which evaluates the relationship between ozone and asthmatic attack. Caution should be exercised in interpreting these personal monitoring maxima, as they are based on a different time scale (five minutes) than are the maxima used in the health effects analyses (one hour), resulting in more sensitivity to variation in the personal monitoring values.

Table II contains the personal monitoring maximum values measured in the indoor and outdoor microenvironments, with vehicles reported separately. The indoor mean is 10.8 ppb, and the outdoor mean is 51.8 ppb. The medians, which are less sensitive to extremes, are 5 ppb for indoors and 42 ppb for the outdoor environment. The rather large range of indoor exposures is indicative of the several individuals included in the personal monitoring who lived in houses which did not have any air conditioning. The maximum exposure in air-conditioned houses was 105 ppb, and only 6% of the values observed were above 20 ppb in these houses. The maximum observed both outdoors and in vehicles is higher than the maxima observed at the fixed sites, indicating the effect of a short term peak exposure as opposed to a one-hour average. The preponderance of personal monitoring measurements were obtained in indoor environments.

The comparison of exposure estimates using both the fixed site data and the exposure model are also shown in Table II. As expected, the fixed site values do not vary much as the individuals move through microenvironments while the exposure model estimates show a much larger variation among the microenvironments. The exposure model indoor estimates appear to be much closer to the observed indoor personal monitoring concentrations, but the range of the estimates is strikingly large. The outdoor and vehicle estimates are seen to be below the observed concentrations.

Table III compares the differences between personal monitoring measures of maximum exposure and exposure estimates based on fixed site measurement and the exposure model. As might be expected, the fixed site measurement performs best when the observed maxima occur outdoors, while the exposure model performs best when the maxima occur indoors. The fixed site exposure estimates average 24.7 ppb above the personal monitoring, while the exposure model averages 14.4 ppb below. The overall mean-squared difference for the exposure model is 1178.7, which is a 46.9% reduction from the mean-squared difference for the fixed site estimates. Much of this reduction is due to the large amount of time the study subjects spent indoors, where the exposure model functions best.

There are three known sources of error in the exposure model. Four of the individuals who took part in the personal monitoring lived in two houses which were unair-conditioned. It can be assumed that the fixed-site-to-indoor regression relationships in these two houses were different from those estimated for air-conditioned houses. These two houses

were the only unair-conditioned residences in the study. Examination of the air-conditioned versus unair-conditioned houses elsewhere[7] indicated that there was a substantial difference in the ability of the exposure model to estimate personal exposures based on the presence or absence of air conditioning. These differences were examined in the current assessment.

For the unair-conditioned houses the fixed site exposure estimate mean-squared difference is 683.2, which is much smaller than the mean-squared difference of 2693.1 for the exposure model estimates. The comparison using the data from the other 26 study subjects who resided in air-conditioned houses shows the opposite effect, with the exposure model mean-squared difference of 965.1 providing a 60.2% reduction when compared to the fixed site estimates.

The second source of error is related to the accuracy of the activity logs. Very short term exposures are reflected in the personal monitoring measurements , which may not have been remembered by study subjects when completing the activity logs. Further, in several subjects, the log data appears to have been shifted by an hour on a few log forms. In either case, there is a misclassification of the microenvironment.

The third source of error stems from the uniform distribution assumption if more than one location was indicated in the activity log. We have chosen to assign equal time to both locations, but the true values would have varied from 1 to 59 minutes. Then, the difference, D, of the "estimated" time weighted average from the "true" time weighted average is

$$D = \frac{(t-30)(O-I)}{60}$$

where O and I are the outdoor and indoor exposure estimates, and t is the time spent outdoors. The expected value of D is

$$E(D) = 0$$

and the variance of D is

$$Var(D) = (.0779)(O-I)^2$$

Table IV shows the results of the comparison of the exposure model and personal monitoring when both sources of data indicate the subject was in the same location. Only the air-conditioned houses have been used. The exposure model and personal monitoring values differed by 7.0 ppb indoors, and 12.7 ppb outdoors. These results indicate that the exposure model, when it is performing at its best, provides an underestimate of the personal exposure maximum of about 7-12 ppb.

As reported elsewhere[7], when the one-hour average ozone concentration obtained from the personal monitoring is compared to the exposure model, an 82.5% reduction in mean squared difference, relative to the fixed site estimate, results. In those analyses, the ozone model underestimated the observed one-hour average ozone concentration by 8 ppb. As the time scale of measurement was the one-hour average for both personal monitoring and exposure model, these comparisons are more stable than those based on maxima.

The failure to detect an air-conditioning difference in light of the large effect this factor has on the error of the exposure model is explained as follows. Of the twelve houses which were monitored, all had some form of air conditioning: ten had central air conditioning and two used window units. The two unair-conditioned houses in the personal monitoring study were totally without any form of air conditioning; they were open to the outside air. Therefore, these house types were not represented in the mobile van study indoor/outdoor monitoring project.

Summary and Conclusions

These results indicate that a substantial reduction in error of exposure estimation for ozone occurs when an exposure modeling technique is used. This model incorporates the recorded activities of the study subjects, the results of fixed, central site monitoring of ambient concentrations of ozone and empirically derived relationships between the fixed site concentrations and those found indoors and outdoors. The primary source of error reduction has not been specifically determined, but our observations indicate that the indoor/outdoor ozone concentrations are dramatically different. This information, combined with knowledge of an individual's location, allows a considerable improvement in exposure estimation for that individual. Further reductions in error may be possible using more distinctions among indoor and outdoor microenvironments and more detailed activity logs, but the added costs are likely to be great.

It appears the exposure estimates used for the health assessment analyses are biased downward by about 7-12 ppb. However, the exposure estimates are a more precise description of the variation in true ozone exposure than those provided by ambient concentrations alone. Therefore, we have reduced the error in estimation of ozone exposure, providing us with a more sensitive analysis of the relationship between ozone exposure and asthma.

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TABLE I

Example of Individual Exposure Estimates for Ozone
for a Twelve Hour Period

Hour Starting Time (CDT)	Hourly Fixed Site Ozone Value (ppb)	Location*		Microenvironment Exposure Estimate Concentrations (ppb)		Hourly Exposure Estimate
		ID	OD	ID	OD	
7	30	1	0	1.6	26.4	1.6
8	37	1	1	1.6	27.1	14.3
9	42	1	0	1.5	31.9	1.5
10	60	0	1	1.6	49.0	25.3
11	87	0	1	1.7	68.9	68.9
12	102	1	0	1.8	86.0	1.8
13	110	1	0	1.8	90.1	1.8
14	115	1	1	1.8	94.6	48.2
15	70	1	0	1.6	61.2	1.6
16	68	1	0	1.6	62.1	1.6
17	57	1	0	1.6	50.7	1.6
18	61	0	1	1.7	49.5	49.5

*ID = indoors; OD = outdoors

Sources of data

Fixed Site Ozone - from monitoring activities

Location - Health and Activity Logs

Estimated Concentrations - Using relationships of fixed site to outdoor and indoor

Exposure estimate - Mean of the estimated concentrations in each location the individual occupied during that hour

TABLE II

Description of Ozone[a] Concentrations in Each of Three Microenvironments As Determined by Personal Monitoring, the Fixed Site Measurements and the Exposure Model

	Indoors	Outdoors	Vehicle
PERSONAL MONITORING			
Mean	10.8	51.8	23.0
Median	5.0	42.0	14.0
Range	1 ; 147	1 ; 250	1 ; 140
Number	249	92	49
EXPOSURE ESTIMATES			
Fixed Site:			
Mean	49.5	44.2	37.4
Median	41.0	44.0	37.0
Range	0 ; 213	1 ; 127	2 ; 81
Exposure Model:			
Mean	4.2	18.6	10.5
Median	1.4	12.3	1.4
Range	.8 ; 81.5	1 ; 77.1	.8 ; 56.3

[a]Ozone is measured in parts per billion.

TABLE III

Summary of Differences Between Personal Monitoring (PM) Ozone[a] Measurements of Maximum Exposure and Ozone Exposure Estimates (Fixed Site or Exposure Model) in Each of Three Microenvironments

	PM - Fixed Site Difference		PM - Exposure Model Difference	
	Mean	MSD[b]	Mean	MSD[b]
Location				
Indoors	-38.7	2896.2	7.2	595.4
Outdoors	7.6	802.3	33.1	2673.9
Vehicle	-14.3	985.4	31.8	1165.7
Overall	-24.7	2219.7	14.4	1178.7

[a]Ozone is measured in parts per billion.

[b]MSD is mean squared difference.

TABLE IV

Summary of Differences Between Personal Monitoring (PM) Ozone[a] Measurements of Maximum Exposure and Exposure Model Estimates for the Air-Conditioned Houses Where Activity Log and Personal Monitoring Locations Agree

	Personal Monitor (Mean)	Exposure Model (Mean)	Difference
Indoors Agree	8.5	1.5	7.0
Outdoors Agree	46.8	34.1	12.7

[a]Ozone is measured in parts per billion.

PLACE		HOURS													
		morning					noon				evening				
		7	8	9	10	11	12	1	2	3	4	5	6	7	
INDOORS	HOME														
	SCHOOL OR WORK														
	ELSEWHERE														
OUTDOORS	IN NEIGHBORHOOD														
	OUT OF NEIGHBORHOOD														
IN OPEN CAR, TRUCK OR BUS															
IN CLOSED CAR, TRUCK OR BUS															

Figure 1. Activity Data Log.

KEYWORDS

Ozone
Exposure Estimation
Microenvironments
Model Validation